MRAS Based Speed Sensorless Vector Controlled Synchronous Reluctance Motor Drive

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Abstract— This study proposes a new speed estimation method based on the Model Reference Adaptive System (MRAS) that calculates the rotor speed and position in a vector controlled Synchronous Reluctance Motor (SynRM) drive. This allows the drive to successfully operate without a speed sensor. In the rotor reference frame (dq-axes), the reactive power 'X' defined in terms of voltages and currents is the functional candidate selected to construct the MRAS system. Reactive power is a good functional choice because it removes the need for stator resistance in the adjustable model, which makes the speed estimator independent of changes in stator resistance. Other than that, the customizable model's speed estimator is devoid of integrator and derivative terms. Furthermore, unlike injection-based speed estimators that are documented in the literature, the speed estimator is hardware-independent and only requires basic processing. Finally, thorough simulations performed using the MATLAB/SIMULINK platform are used to confirm the efficacy of the suggested speed estimator. Simulation results have been verified through HIL 402 real-time simulator.

Index Terms- MRAS, Reactive Power, Sensorless, SynRM, Vector Control

I. INTRODUCTION

SYNCHRONOUS Reluctance Motors (SynRM) have gained popularity in the past year due to their notable characteristics, which include efficiency, a strong torque density, and a manufacturing method that is comparable to that of Induction Motors (IM). Furthermore, since the cost of the rare-earth minerals used in permanent magnet (PM) machines is unpredictable, the SynRM may prove to be a more affordable option than its equivalents, the PM Synchronous Machines (PMSM). Aside from that, SynRM's benefits in terms of price, robustness, and output power have drawn attention [1],[3].

While the interior of the stator is cylindrical in shape, the rotor of SynRM is of the salient pole type. There is no copper in the rotor since it lacks a field winding. The rotor has no copper loss. It runs at really fast speeds as well. By removing some of the rotor teeth from a conventional squirrel cage rotor, SynRM achieves the rotor's saliency. Due to the low value of (Ld/Lq), such traditional have low saliency and poor torque density. Recently, rotors have been developed with a sturdy and dependable construction. Thus, flux barrier, segmental, and axially laminated rotors are the three basic types [4]. Axially laminated materials have a greater ratio of (Ld/Lq), i.e. 8–10, which improves the torque density [2]. As a result, SynRM can be used as a substitute for PM machines and IM.

Reluctance torque is produced by the SynRM because it functions according to the minimum reluctance law. The vector control of all machine drives is now a better option due to advancements in processor technology. It is clear that vector-controlled drives function dynamically quickly, therefore applying a vector control method to SynRM makes sense. The rotor speed in SynRM's vector control can be determined by a sensor or an estimating method. A speed sensor's use may result in a number of issues, including mounting, aging, signal transmission, dependability, etc. It is also less expensive to remove the speed sensor. Therefore, it is more appreciated in industrial applications when the speed sensor is eliminated. The literature currently has a few methods for estimating the position and speed of the SynRM [5]-[8], [16].

There are numerous techniques for calculating position and speed at low speeds, but some of them have issues such excessive stator current flow based on the various motor states [8]. The Back-EMF method is a traditional speed estimation technique that struggles to predict shaft speed in the low-speed region [9][16]. Additionally, certain techniques exist for estimating speed in the low-speed zone, but they necessitate an additional hardware configuration, such as methods based on Signal Injection (SI) [5]. This isn't a workable solution because it will cost more and take up more space.

The standard voltage is injected with a high-frequency sinusoidal signal of constant amplitude in the SI-based technique [5] [10], producing an extra 600 Hz current. We estimate the speed from the 600Hz current after it has been demodulated. Another popular technique for estimating speed is the Flux Observer based method, which is categorized as a Model-Based technique and heavily relies on the machine's stator resistance [7]. Therefore, this approach will not function well when there are parameter variations, particularly when there is a stator resistance variation. The Extended Kalman filter based Observer is another technique used in the speed estimation process. This speed estimation technique is only useful in the high-speed range of roughly 20,000 rpm; it also depends on the machine's stator resistance and apart from it faces conversion issues [6].

This work proposes a vector controlled SynRM drive speed estimation technique based on the Model Reference Adaptive System (MRAS) that provides satisfactory speed estimates in both low and high speed operating regions. This approach is straightforward, requires less hardware, signal processing, etc. The majority of speed estimation methods rely on the machine's stator resistance. The speed estimation technique will be affected by changes in stator resistance during machine operating conditions. However, the suggested approach is completely unaffected by stator resistance; as a result, speed is computed with excellent accuracy even in the presence of stator resistance change.

Ultimately, a thorough simulation of the speed sensorless vector is used to validate the efficacy of the speed estimator.

II. MATHEMATICAL MODELLING OF SYNCHRONOUS RELUCTANCE MOTOR

A. Voltage and Torque equations

The machine model in ABC (3-phase) reference frame

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{bmatrix}$$

Where V_a, V_b, V_c are machine voltages, i_a, i_b, i_c are the machine phase currents, R is the machine phase resistance and magnetic flux associated with each phase are represented by φ. The voltage equations of the machine can be given in the rotor reference frame (dq-axes) as [11],

$$\frac{di_{ds}}{dt} = \frac{v_{ds}}{L_d} - \frac{i_{ds}R_s}{L_d} + \frac{\omega_e L_q i_{qs}}{L_d}$$

$$\frac{di_{qs}}{dt} = \frac{v_{qs}}{L_q} - \frac{i_{qs}R_s}{L_q} - \frac{\omega_e L_d i_{ds}}{L_q}$$

The electromagnetic torque is developed by the interaction ofthe space vector of stator flux linkage and space vector of stator current [4]. Since rotor current is absent so stator flux linkages are established by stator current only. The electromagnetic torque equation is given as,

$$T_e = \frac{3}{2} P\left(L_{ds} - L_{qs}\right) i_{ds} i_{qs}$$

Where, P is the no of pole pairs. The mechanical equation of the motor is given by-

$$J \frac{d}{dt}\omega_r = T_e - T_L - B\omega_r$$

Where J is the moment of inertia and B is the viscous co-efficient.

B. Equivalent Circuit in d-q Reference Frame

The equivalent circuit diagram of SynRM in the rotating frame (d-q frame) is as shown in Fig.2. The q-axis voltage depends on the voltage drop across stator resistance (Rs), the voltage induced in the q-axis inductance and total flux along the d-axis. Whereas, d-axis voltage depends on the voltage drop across stator resistance (Rs), the voltage induced in the d-axis inductance and total flux along q-axis.

$$v_{qs} = R_s i_{qs} + \omega_e \psi_{ds} + L_{qs} \dot{i}_{qs}$$

$$v_{qs} = R_s i_{qs} + \omega_e L_{ds} i_{ds} + L_{qs} \dot{i}_{qs}$$

$$v_{ds} = R_s i_{ds} - \omega_e \psi_{qs} + L_{ds} \dot{i}_{ds}$$
$$v_{ds} = R_s i_{ds} - \omega_e L_{qs} i_{qs} + L_{ds} \dot{i}_{ds}$$

$v_{ds}, v_{qs}, i_{ds}, i_{qs}$ and R_s represents the d-q stator voltage, currents, and stator resistance with reference to the rotor reference frame. Rs is the stator resistance. Lds and Lqs are d-axis and q-axis inductances respectively.

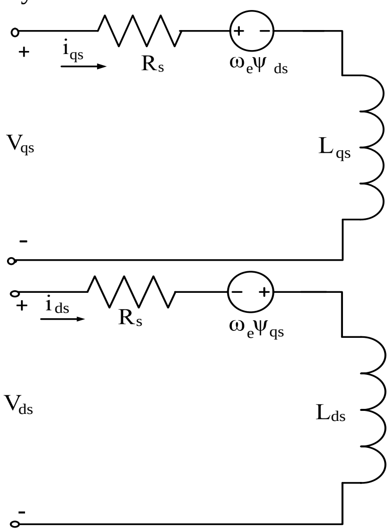


Fig. 1: Equivalent circuits of SynRM: (a) along d-axis (b) along q-axis

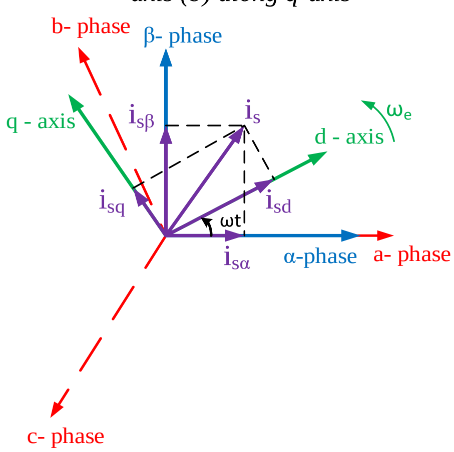


Fig. 2: Different coordinate reference-frames for SynRM

C. Vector Control Techniques of Synchronous ReluctanceMachine

The three-phase current in vector control can be shown as two orthogonal vector i_{ds} and i_{qs}. For SynRM drive, there are primarily two kinds of vector control schemes: constant current angle control and constant direct axis current control. Three distinct methodologies are generally used for constant current angle control: maximum power factor control, quickest torque control, and greatest torque per ampere control [4] [12]. This work limits the control to constant direct axis current (i_{ds}) control, where ids is assumed to be constant up to base speed. The conversion of 3-phase AC currents to d-q -axis (rotor reference frame) by using Clarke transformation.

$$\begin{bmatrix} i_{qsr} \\ i_{dsr} \end{bmatrix} =$$
$$\frac{2}{3}\begin{bmatrix} \cos\omega_r t & \cos(\omega_r t - \frac{2\pi}{3}) & \cos(\omega_r t + \frac{2\pi}{3}) \\ \sin\omega_r t & \sin(\omega_r t - \frac{2\pi}{3}) & \sin(\omega_r t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix}$$

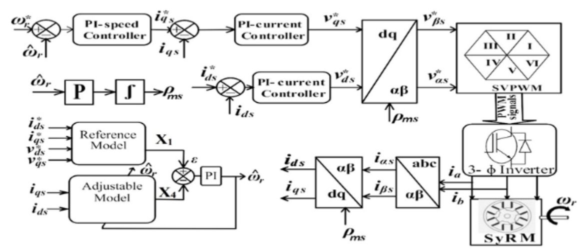


Fig 3: Vector control of SynRM drive with MRAS speed estimator

Constant d-axis Current (i_{ds}) Control

In the elementary control method, d-axis current is taken as constant and q-axis current is controlled to control torque up to the base speed i.e in the constant torque region [1],

$$i_d^* = K$$

Where,

$$K = \frac{\psi_{smax}^*}{\sqrt{2}}$$

And,

$$\psi_{smax}^* = \sqrt{\frac{4\,|T_e^*| L_d L_q}{3P(L_d - L_q)}}$$

Where P is the number of pole pair. Above the base speed, the d-axis current needs to be decreased to achieve high-speed performance [2]. Therefore, it can be calculated as-

$$i_d^* = K\frac{\omega_b}{|\omega_r|}$$

Where, ω_b is the base speed and ω_r is the rated speed. The torque of the motor is given by the expression-

$$T_e = \frac{3}{2}P(L_{ds} - L_{qs})i_{ds}i_{qs}$$

Fast Torque Response Control-
In this control scheme, it is required to have the fastest torque response control. Of the drive. The above equation can be further modified by multiplying with a square of the stator flux. The stator flux can be given by the expression-

$$\widehat{\psi_s} = \sqrt{(L_{qs}^2 i_{qs}^2) + (L_{qs}^2 i_{qs}^2)}$$

Now,

$$T_e = \frac{3}{2}P\frac{(L_{ds} - L_{qs})i_{ds}i_{qs}\widehat{\psi_s^2}}{(L_{ds}^2 i_{ds}^2) + (L_{qs}^2 i_{qs}^2)}$$

Which can be written as-

$$T_e = \frac{3}{2}P\frac{(L_{ds} - L_{qs})\psi_s^2 \tan\theta}{L_{ds}^2 + L_{qs}^2(\tan\theta)^2}$$

Where$\tan\theta = \frac{i_{qs}}{i_{ds}}$, the above torque expression is a function of 'θ' and the stator flux (ψ_s). The fastest torque response is obtained at maximum torque. To get fastest torque response we differentiate T_e with respect to tanθ at a given stator flux and equating it to zero. We get,

$$\tan\theta = \frac{L_{ds}}{L_{qs}}$$

Therefore, the above equation can also be related as-

$$\frac{i_{qs}}{i_{ds}} = \frac{L_{ds}}{L_{qs}}$$

To get the fastest torque control above condition must satisfied.

III. PROPOSED SPEED ESTIMATION TECHNIQUE

Figure 3 illustrates the speed estimation method that has been suggested. While the adjustable model evaluates the simplified equation for reactive power under steady state and is a direct function of the quantity to be estimated, the reference model evaluates the defining equation of reactive power independent of the rotor speed. The two models' output quantities are compared to produce an error signal, which is then supplied to a PI controller, an adaptation mechanism that produces an estimated quantity (rotor speed) as its output. This estimated speed is then utilized to fine-tune the adjustable model so that the estimated speed approaches the machine's actual speed and the error between the two models disappears [14, 15]. The actual instantaneous reactive power of the machine is given as-

$$X_1 = V_{qs}i_{ds} - V_{ds}i_{qs}$$

The above equation is taken as the reference model in our proposed estimation technique.
Since,

$$v_{ds} = R_s i_{ds} - \omega_e\psi_{qs} + L_{ds}\dot{i_{ds}}$$

$$v_{qs} = R_s i_{qs} + \omega_e\psi_{ds} + L_{qs}\dot{i_{qs}}$$

Where, ψ_{ds} and ψ_{qs} are the d- and q-axis stator fluxes.
At steady state,

$$\dot{i_{ds}} = \dot{i_{qs}} = 0$$

Therefore, on modification-

$$V_{ds} = i_{ds}R_s - \omega_e\psi_{qs}$$

$$V_{qs} = i_{qs}R_s + \omega_e\psi_{ds}$$

Substituting V_{ds} and V_{qs} into equation of Y, we get,

$$X_2 = i_{ds}\psi_{ds}\omega_e + i_{qs}\psi_{qs}\omega_e$$

Since, $\psi_{ds} = L_{ds}i_{ds}$ and $\psi_{qs} = L_{qs}i_{qs}$
Substituting ψ_{ds} and ψ_{qs} in Eq. (3.6), we get,

$$X_3 = \omega_e[L_{ds}i_{ds}^2 + L_{qs}i_{qs}^2]$$

$$X_4 = \omega_r\left(\frac{P}{2}\right)[L_{ds}i_{ds}^2 + L_{qs}i_{qs}^2]$$

The above equation is taken as the adjustable model in our proposed estimation technique. As we can see the adjustable model is independent of stator resistance and it is a function of electrical speed. The speed of the motor can be evaluated as-

$$\widehat{\omega_r} = K_P(X_4 - X_1) + K_I\int(X_4 - X_1)\,dt$$

IV. SIMULATION RESULTS

A. Variable speed operation including standstill Operation

Since the suggested speed estimation is independent of stator resistance, it has very high accuracy when the speed is at zero. According to the simulation results, the motor is run at its rated speed and ramped down to zero at no load, half the rated load, and full load. During the standstill operation a sudden change in load from 50% to 100% of the rated load occurs at t=100 sec, that can be seen from Fig. 4 (i_{qs}).

With a high degree of precision, the speed can be estimated using the suggested speed estimation algorithm. After t=70 seconds, the rotor's position (or angle) is also displayed; the estimated and actual positions match. As a result, the suggested speed estimate methods, which are depicted in Fig. 5, can also operate at zero speed when operating at full load.

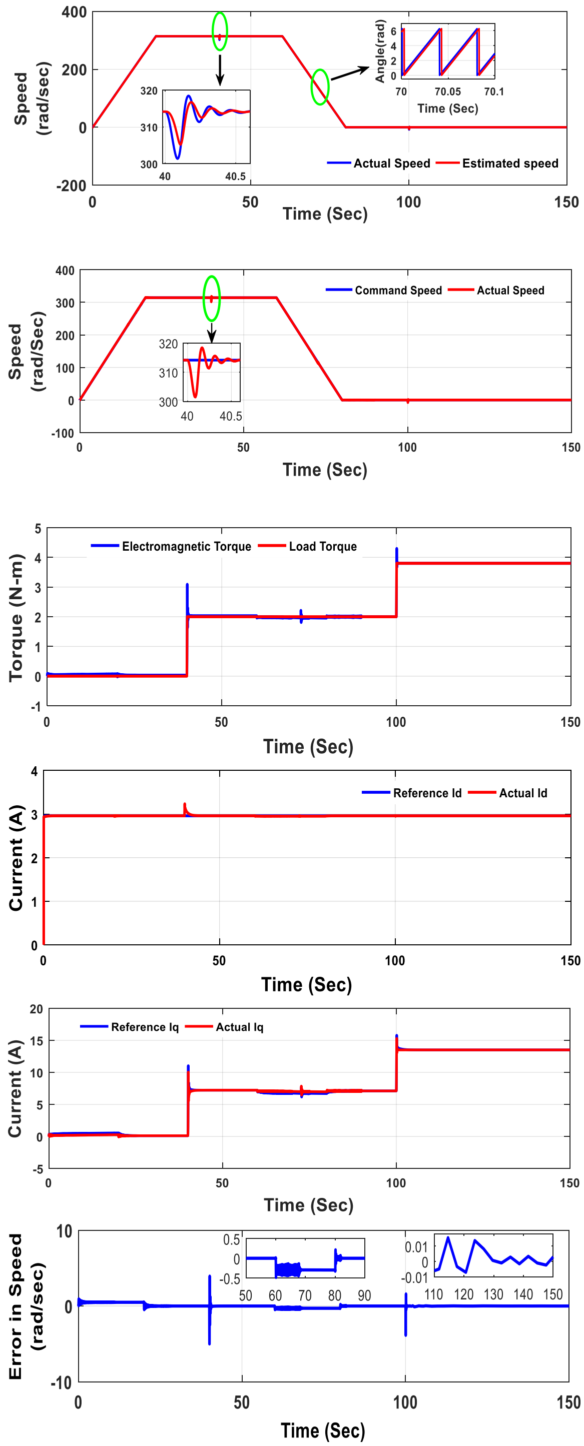
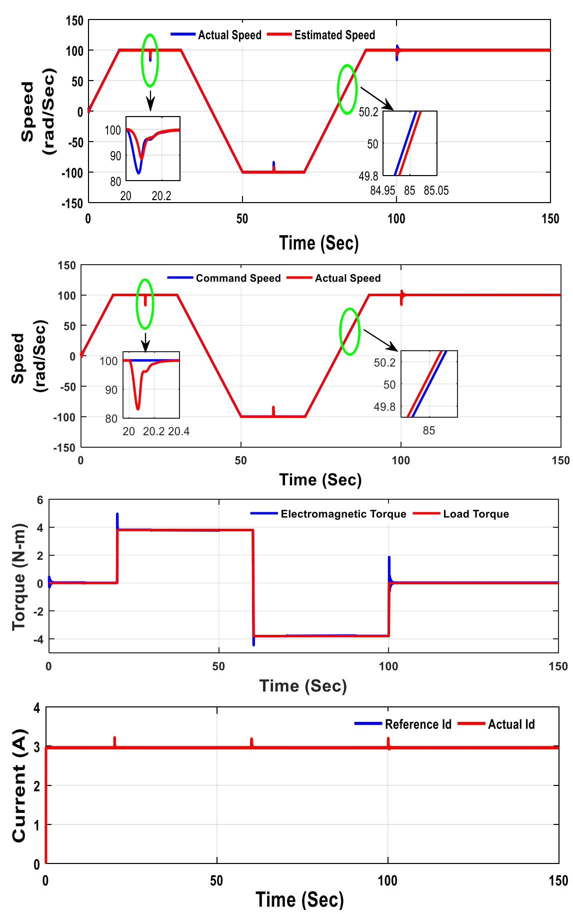


Fig. 4: Simulation results for variable speed motoring operation including standstill condition at step change of load: (a) actual and estimated speed, (b) command and estimated speed, (c) Electromagnetic torque and load torque, (d) d-axis reference and actual current (e) q-axis reference and actual current (f) Error in Actual and Estimated Speed

B. Four Quadrant Operation

Fig. 5 illustrates the SynRM drive's 4-quadrant speed control at rated load and is viewable from both speed and i_{qs}. The rotor's real speed decreases and returns to the reference speed as a result of an abrupt change in load. During the transient, there is less discrepancy between the estimated and real speeds. However, the inaccuracy is almost nil at a steady-state. The adaptation mechanism can be fine-tuned to increase this performance. As we can see, during the drive's full 4-quadrant operation, the projected speed and real speed are nearly identical. The suggested method functions effectively in both regenerative and driving modes.



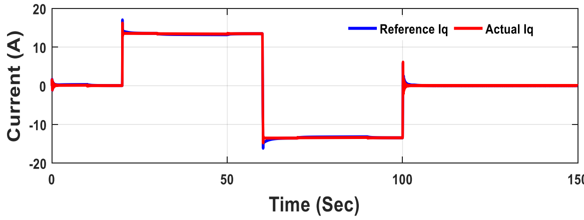
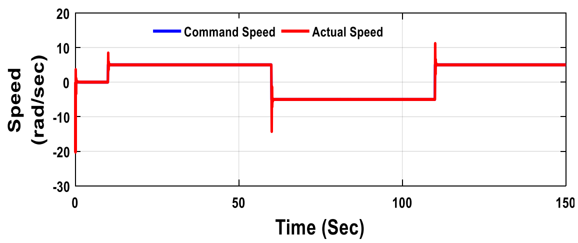
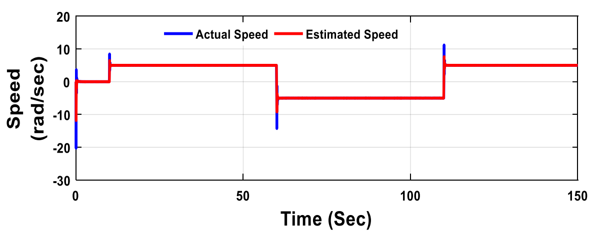


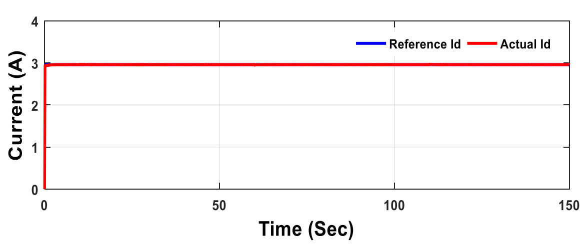
Fig. 5: Simulation results for four-quadrant operation of SynRM (a) actual and estimated speed, (b) command and estimated speed, (c) Electromagnetic torque and load torque, (d) d-axis reference and actual current, (e) q-axis reference and actual current

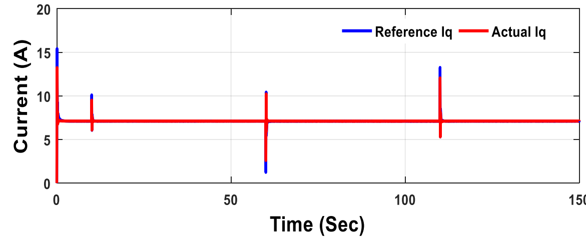
C. Speed Estimation Under Step Change in Motor Speed

Step changes in the motor's speed are possible in unfavourable conditions. The simulation result in Figure 6 illustrates how precisely the suggested speed estimation technique calculates speed under these conditions. Here, the speed is varied from zero to five rad/sec, then to five rad/sec, and so on, while a constant torque is provided from the beginning.









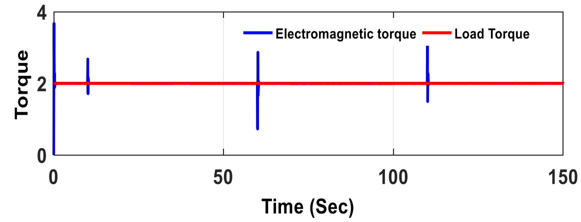
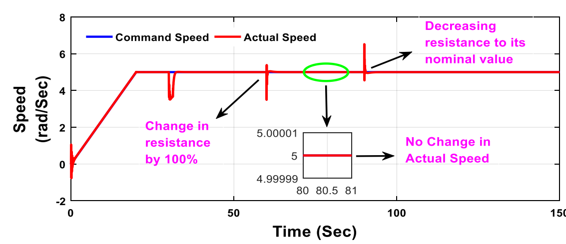
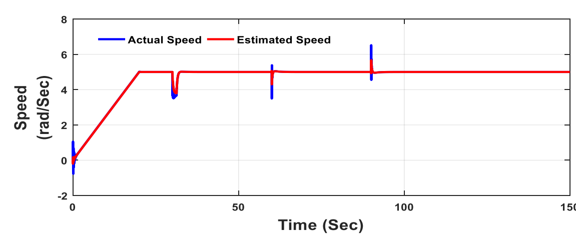


Fig. 6: Simulation results under step change of motor speed at constant load: (a) Command and actual Speed, (b) actual and estimated speed, (c) d-axis reference and actual current, (d) q-axis reference and actual current, (e) Electromagnetic torque and load torque

D. Variation in Resistance at Low Speed

As seen by the simulation results in Fig. 7, the suggested speed estimation algorithm remains unaffected even when the machine's stator resistance varies, particularly at low speeds and under load variation conditions. The stator resistance will fluctuate over the machine's extended lifespan.





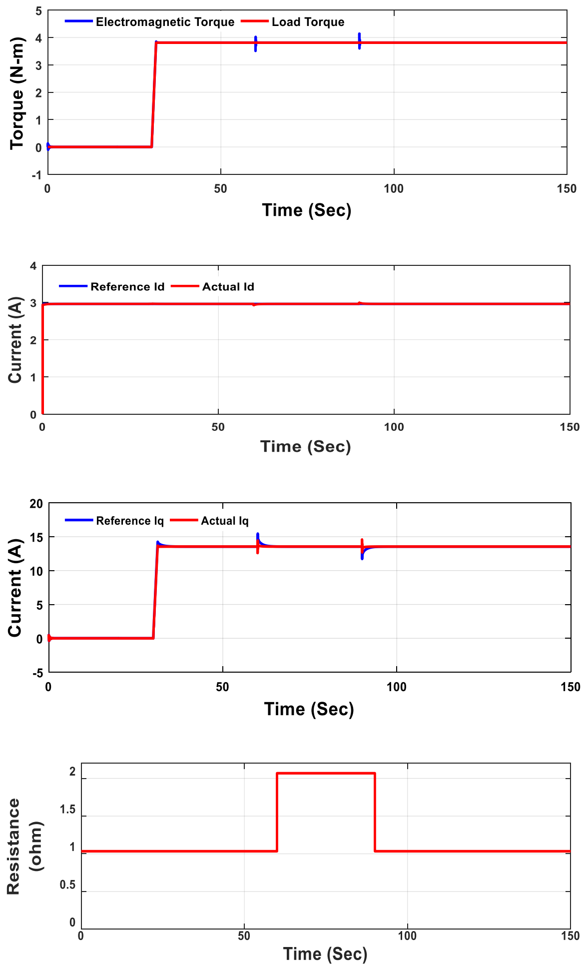
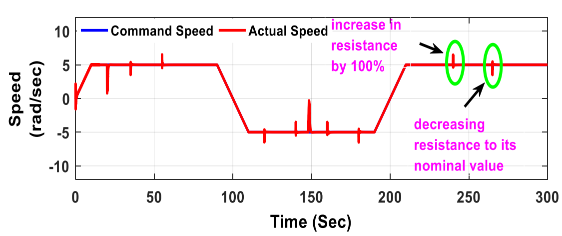


Fig. 7: Simulation results of the effect of resistance variation at low speed: (a) Command and actual Speed (b) actual and estimated speed (c) Electromagnetic torque and load torque (d) d-axis reference and actual current (e) q-axis reference and actual current, (f) Resistance variation at low speed

E. Variation in Resistance in all the four quadrant at low speed

As we can see in the simulation results as shown in Fig. 7(f), we have change stator resistance by 100% in all four quadrants at low speed, but there is no effect of resistance variation in all the four quadrants.



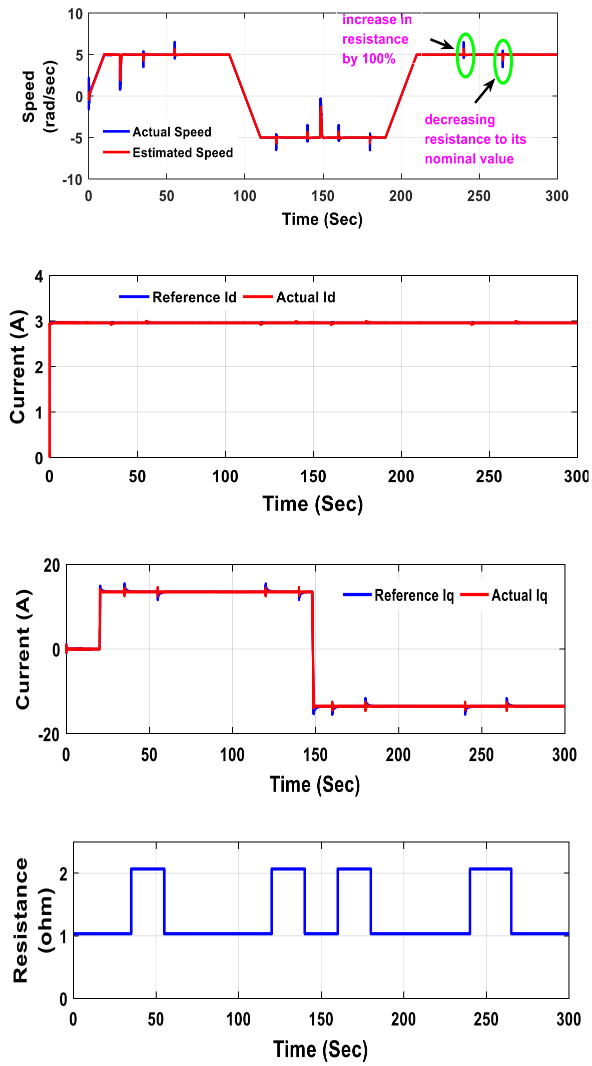


Fig. 8: Simulation results of the effect of resistance variation at low speed: (a) Command and actual Speed, (b) actual and estimated speed, (c) d-axis reference and actual current, (d) q-axis reference and actual current, (e) Resistance variation at low speed in all the four quadrant

V. HARDWARE VALIDATION

The typhoon HIL 402 has inbuilt electrical machine models, inverter, sensors and voltage sources which acts as a hardware device. The typhoon DSP interface acts as a digital interface for calibration and control. The vector controlled SynRM drive is validated in Typhoon HIL 402.

Fig. 9: HIL device and its interface

The speed estimation model for a vector-controlled drive is designed in HIL schematic editor as shown in Fig. 9 dumped in to real time typhoon HIL and experiment was conducted and verified.

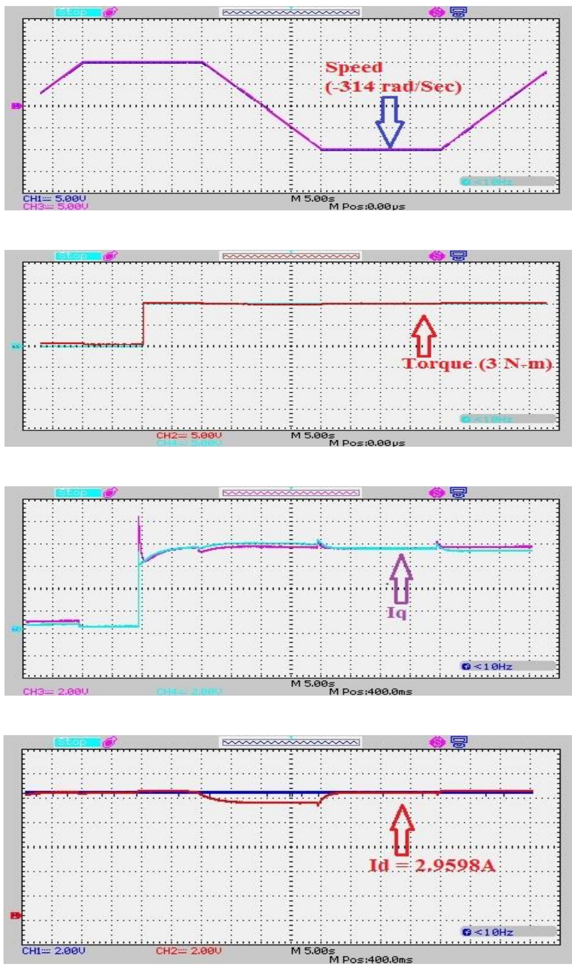
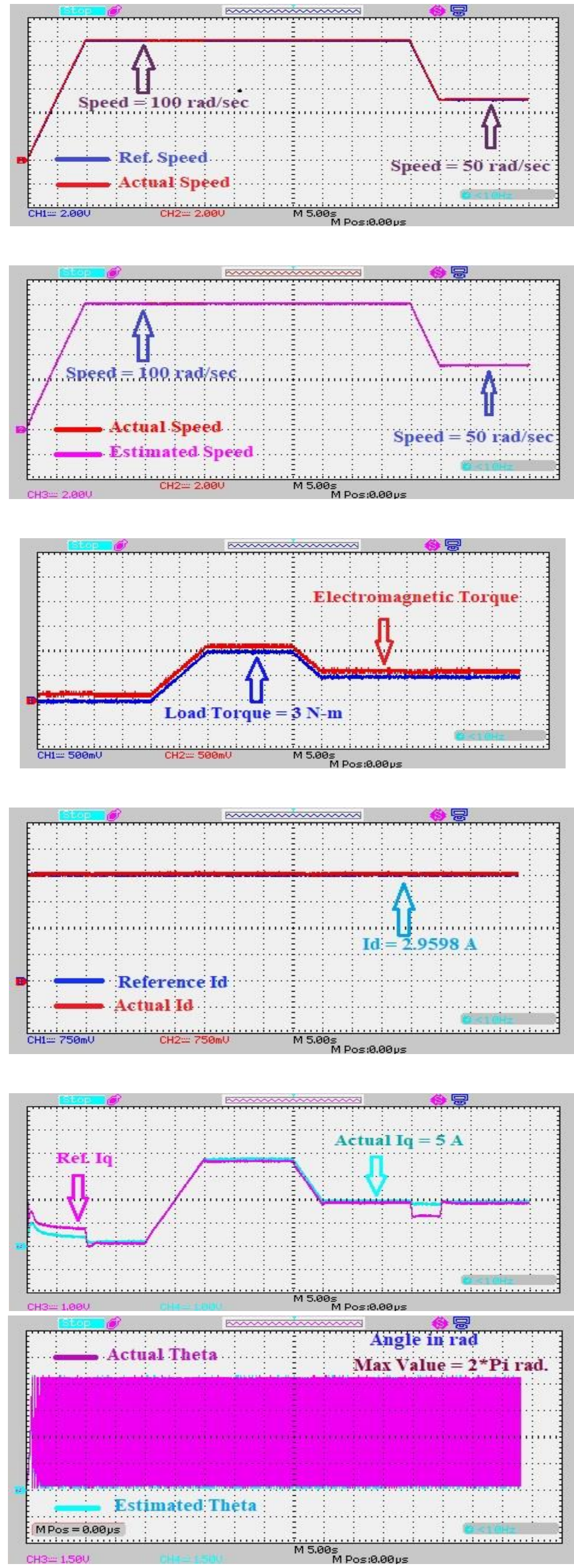


Fig. 10: HIL results of vector controlled SynRM: (a) four quadrant speed change with ramp Command (b) step change of torque (c) q- axis current (d) d-axis current

The speed of the motor increases with ramp command and at constant speed, torque is applied with ramp change then after some time torque decreases with ramp change and maintained constant of value T=1.5 N-m after t= 50 sec. With constant torque of value 1.5 N-m speed starts to decrease with ramp change.



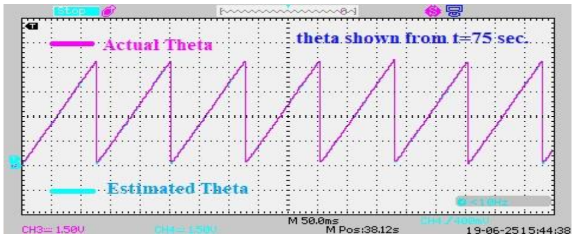
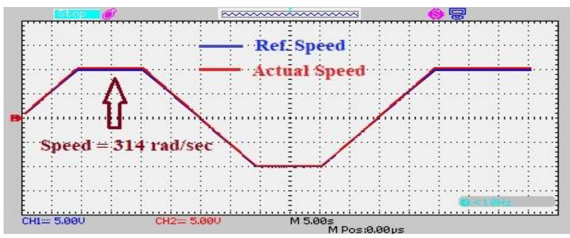
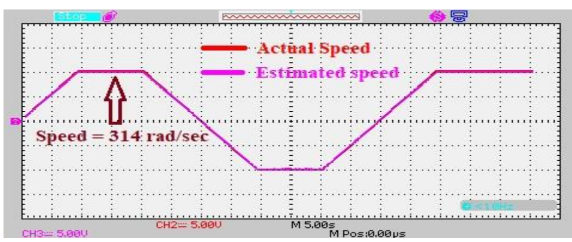
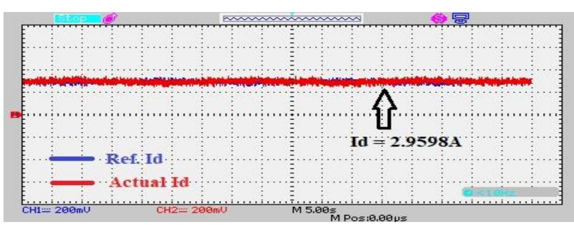


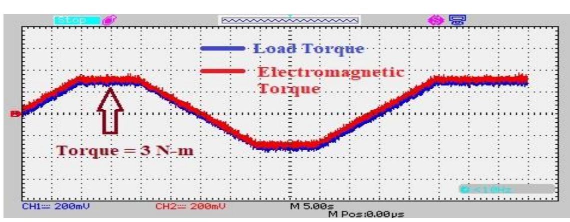
Fig. 11: HIL Results for speed sensorless vector control SynRM. (a) command and actual speed. (b) actual and estimated speed. (c) Load torque and electromagnetic torque (d) d-axis stator current (e) q-axis stator current (f) Position (i.e angle) of the rotor (g) position of rotor in the expanded form of SynRM drive

Change in Torque proportional to Speed,









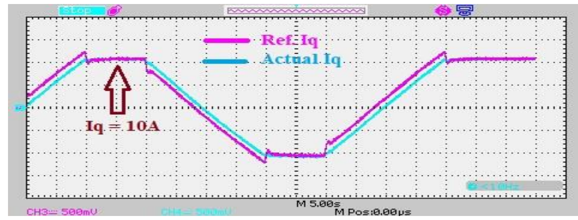


Fig. 12: HIL Results for speed sensorless vector control SynRM (a) Command and actual Speed (b) actual and estimated speed (c) d-axis stator current (d) load tprque and electromagnetic torque (e) q-axis stator current of SynRM drive.

Table I – Parameters of the SynRM

Rated Voltage	415 V
Speed	3000 rpm
Power	4.0 kw
Rated current	9.8 A
Rated Torque	12.7 N-m
Ld	72.92 mH
Lq	9.54 mH
R	1.034 ohm
No. of poles	2
J	0.00276 Kg-m2

CONCLUSION

For a vector-controlled SynRM drive, a novel speed estimator is suggested that uses reactive power as the functional candidate for building the MRAS reference and adjustable models. It is discovered that the suggested speed estimator is hardware-independent and requires less signal processing, even in the absence of the machine's stator resistance. MATLAB simulations demonstrate that the speed estimator operates effectively in each of the four operating quadrants. Future work on this project will focus on making the suggested speed estimation completely independent of the parameters.

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